TITLE

METHOD OF COMPENSATING FOR TILT AND/OR DEFOCUS AND
APPARATUS THEREFOR

CROSS-REFERENCE TO RELATED APPLICATIONS

5   This application claims the benefit of Korean Application Nos. 99-24297, filed June 25,

1999; 99-38398, filed September 9, 1999; and 99-38399, filed September 9, 1999, in the

Korean Industrial Property Office, the disclosures of which are incorporated herein by

reference.

BACKGROUND OF THE INVENTION

10   1.   Field of the Invention

         The present invention relates to a method of compensating for tilt and/or defocus and an

apparatus therefor, and more particularly, to a method of compensating for tilt and/or defocus

by controlling the power and/or time required for recording according to the amount of tilt

and/or defocus of an optical recording medium, and an apparatus therefor.

15   2.   Description of the Related Art

         When tilt or defocus occurs, or tilt and defocus occur at the same time in an optical disc

which requires high density recording using a blue light laser, the effect of the tilt and/or

defocus increases in comparison to the effect on a low density recording, which uses a red light

laser. Therefore, a method of compensating for the effect is required.

20   When both an objective lens with a large numerical aperture (NA) and a blue light laser

using a 400 nm short wavelength is used instead of using an existing red light laser (650 nm

wavelength) in order to obtain a higher density, a system is affected as shown in Table 1, as

follows. The factor which most affects recording is a reduction in the margin according to the

increase in tilt and a shallowing of the focal depth.

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Table 1

Item	Effect	NA 0.6	NA 0.65	NA 0.85	Effect in NA 0.6 NA 0.85
Spot diameter (relative size)	λ/NA	1	0.93	0.70	Capacity doubled
Focal depth (relative depth)	λ/NA^2	1	0.85	0.50	Servo control bandwidth doubled
Disc tilt (relative margin amount)	λ/tNA^3	1	0.79	0.35	Strict disc tilt allowance
Disc thickness change (relative allowance)	λ/NA^4	1	0.73	0.25	Strict thickness allowance in disc manufacturing

In addition, tolerances for radial tilt and tangential tilt in a current digital versatile disc-random access memory (DVD-RAM) are 0.7°and 0.3°, respectively. The basic characteristics of a disc must be met while remaining within these tolerances. Thus, for example, power, such as write power and erase power, must be maintained at a level which is sufficient to obtain the write characteristics defined in a disc specification.

However, when a blue light laser using a short wavelength (400 nm) is used to meet the increasing demand for high density recording, the effect of tilt becomes greater. That is, when a higher NA is used in order to obtain the same substrate thickness and high density, the value of coma aberration becomes much greater. Equation 1 expresses the coma aberration as follows:

$$Comma\ Aberration = (\frac{n^{2-1}}{2n^3}*d*\frac{NA^3}{wavelength})*(tilt*\frac{\pi}{180}).....(1)$$

where, n is the refractivity of a substrate, d is the thickness of the substrate, and NA is the numerical aperture of an objective lens.

FIG. 1 illustrates coma aberration in three dimensions according to wavelength and NA, when the thickness of a substrate is 0.6 mm, the refractivity of a substrate is 1.5, and tilt is 0.5°, using the equation 1. The figure shows that coma aberration increases as wavelength becomes shorter and numerical aperture becomes greater.

FIG. 2 illustrates the changes in beam peak intensity with respect to tilt. According to FIG. 2, as tilt increases, the recording beam peak intensity decreases at a wavelength of 400 nm more rapidly than at a wavelength of 650 nm. If recording is performed under this condition, the desired length and width of a recording mark cannot be recorded. As the NA increases, beam peak intensity decreases even at the same wavelength of 400 nm and 0.6 mm substrate thickness (t).

FIG. 3 illustrates changes in beam spot size with respect to tilt the beam spot size normalized by the beam size when tilt is 0° (Beam width$_{tilt}$/beam width$_{tilt=0}$). The figure shows that as tilt increases, spot size increases more at a wavelength of 400 nm than at a wavelength of 650 nm, and, as NA increases, spot size increases even at the same wavelength of 400 nm.

FIG. 4 illustrates changes in the maximum temperature-to-write power ratio (Tmax) with respect to tilt, with Tmax normalized by Tmax when tilt of 0° (Tmax$_{tilt}$/Tmax$_{tilt=0}$). The figure shows that as tilt increases, Tmax decreases more rapidly at a wavelength of 400 nm than at a wavelength of 650 nm, and, as write power (P$_w$) increases, Tmax decreases even at the same wavelength of 400 nm, while at a wavelength of 650 nm, Tmax is insensitive to changes in write power (P$_w$).

In addition, as the luminance effect of a short wavelength laser diode decreases when the power emitted therefrom changes according to the temperature change, the laser diode must

emit luminance stably in order to read information recorded on a disc without error and to increase the reliability of an optical disc system.

FIG. 5 illustrates changes in Tmax with respect to tilt with Tmax normalized by Tmax for a tilt of $0°$ ($Tmax_{tilt}/Tmax_{tilt=0}$). As in FIG. 4, FIG. 5 shows that as tilt increases, Tmax decreases more rapidly at a wavelength of 400 nm than at a wavelength of 650 nm. In addition, as write time (T_w) increases, Tmax decreases even at the same wavelength of 400 nm, while at a wavelength of 650 nm, Tmax is insensitive to changes in (T_w).

Accordingly, since beam intensity decreases rapidly and the beam spot size increases at a wavelength of 400 nm with respect to tilt, the desired length and width of a recording mark cannot be obtained when recording, and therefore, power density ultimately decreases. In addition, when recording is performed on a disc that requires high density, a 400-nm wavelength laser beam is used and tilt compensation is required since the required temperature for forming an amorphous mark decreases rapidly with respect to tilt as shown in FIGS. 4 and 5.

One known method of compensating for tilt extends the tilt margin by, during disc manufacture, thinning the substrate thickness, which is currently 0.6 mm. However, since having a substrate thickness less than 0.6 mm causes problems in manufacturing and in disc characteristics, tilt compensation cannot be performed simply by manufacturing a substrate thinner than 0.6 mm. In addition, as the focal depth of the incidence beam becomes shallower, the defocus margin becomes smaller, which causes recording problems since recording is sensitive to even a small degree of defocus. This will now be explained referring to FIGS. 6 and 7, showing beam intensity and spot size, respectively, with respect to defocus in red wavelength and blue wavelength.

FIG. 6 illustrates changes in beam peak intensity with respect to defocus, and with the beam peak intensity normalized by beam peak intensity when defocus is $0°$. As defocus increases, incidence beam intensity decreases more rapidly at a wavelength of 400 nm and 0.65 NA than at a wavelength of 650 nm and 0.6 NA. When recording is performed in this

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condition, the desired length and width of a recording mark cannot be recorded. In addition, as NA increases, beam intensity decreases even in the same wavelength.

FIG. 7 illustrates changes in beam spot size with respect to defocus, with spot size normalized by spot size when defocus is 0. As defocus increases, spot size increases more at a

5   wavelength of 400 nm than at a wavelength of 650 nm. As NA increases, spot size increases even for the same wavelength.

Therefore, like the effect of tilt, defocus affects both the peak intensity and the spot size such that normal recording cannot be performed. In addition, simultaneous occurrence of defocus and tilt is a more serious problem. The beam shape, peak intensity, and spot size in

10   the simultaneous occurrence of defocus and tilt are shown in FIGS. 8 and 9.

FIG. 8 illustrates changes in beam profile when both defocus and tilt occur at the same time. Curve 1 shows a normal-state beam shape; curve 2 shows the beam shape when defocus is 0.25 μm; curve 3 shows the beam shape when defocus is 0.5 μm; curve 4 shows the beam shape when tilt is 0.5°; curve 5 shows the beam shape when tilt is 0.5° and defocus is 0.25

15   μm; and curve 6 shows the beam shape when tilt is 0.5° and defocus is 0.5 μm.

FIG. 9 illustrates changes in beam spot size and peak power intensity when defocus and tilt occur at the same time. The abscissa shows a normal case 1, a case 2 where defocus is 0.25 μm, a case 3 where defocus is 0.5 μm, a case 4 where tilt is 0.5°, a case 5 where tilt is 0.5° and defocus is 0.25 μm, and a case 6 where tilt is 0.5° and defocus is 0.5 μm. The

20   ordinate shows both the normalized value of peak intensity when tilt and defocus occur for peak intensity in a normal state, and the normalized value of spot size when tilt and defocus occur for spot size in a normal state. As defocus and/or tilt increase, peak power intensity decreases, and spot size increases. Peak power intensity decreases more, and spot size increases more, when tilt and defocus occur at the same time than when they occur

25   individually.

As shown in FIGS. 8 and 9, when tilt and defocus occur at the same time, the effect is more serious than when tilt or defocus occurs singly. Accordingly, there is a need to compensate for tilt and/or defocus while performing high density recording.

SUMMARY OF THE INVENTION

5   To solve the above problems, it is an object of the present invention to provide a method of compensating for tilt in which recording is performed by adjusting power and/or time used for recording with respect to the tilt of an optical recording medium.

It is another object to provide a method of adaptively compensating for a write pulse with respect to the detected tilt of an optical recording medium.

10   It is another object to provide a method of adaptively compensating for a write pulse with respect to the detected defocus of an optical recording medium.

It is another object to provide a method of compensating for tilt and defocus in which recording is performed by adjusting power and/or time required for recording with respect to the tilt and defocus of an optical recording medium.

15   It is another object to provide a method of compensating for detected tilt after detected defocus is compensated.

It is another object to provide a method of adaptively compensating for the recording pattern of a write pulse with respect to detected tilt and/or defocus of an optical recording medium.

20   It is another object to provide an apparatus for compensating for tilt in which recording is performed by adjusting the power and/or time used for recording with respect to tilt of an optical recording medium.

It is another object to provide an apparatus for adaptively compensating for a write pulse with respect to the detected tilt of an optical recording medium.

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It is another object to provide an apparatus for compensating for tilt and/or defocus in which recording is performed by adjusting power and/or time required for recording with respect to tilt and/or defocus of an optical recording medium.

It is another object to provide an apparatus for compensating for detected tilt after detected defocus is compensated.

It is another object to provide an apparatus for adaptively compensating for the recording pattern of a write pulse according to the detected tilt and/or defocus of an optical recording medium.

Additional objects and advantages of the invention will be set forth in part in the description which follows and, in part, will be obvious from the description, or may be learned by practice of the invention.

To accomplish the above objects of the present invention, there is provided a method of compensating for tilt of an optical recording medium , the method including detecting the tilt of the optical recording medium; and compensating a recording signal having a predetermined recording pattern using a predetermined scheme with respect to the detected tilt.

To accomplish another of the objects of the present invention, there is provided a method for compensating for defocus of an optical recording medium which can record and rewrite data, the method including detecting the defocus of the optical recording medium; and performing compensating recording by a predetermined scheme with respect to the detected defocus.

To accomplish another of the objects of the present invention, there is provided a method of compensating for tilt and defocus of an optical recording medium, the method including detecting defocus of the optical recording medium; compensating for a write pulse having a predetermined recording pattern by a predetermined scheme with respect to detected defocus; detecting the tilt of the optical recording medium; and compensating write pulse having a predetermined recording pattern with respect to the detected tilt.

To accomplish another of the objects of the present invention, there is provided an

apparatus for compensating for tilt which records and/or reproduces information on an optical recording medium, the apparatus having a tilt detector for detecting the tilt of an optical recording medium; and a recording compensator for compensating the recording signal having a predetermined recording pattern, using a predetermined scheme with respect to tilt detected by the tilt detector.

To accomplish another of the objects of the present invention, there is provided an apparatus for compensating for tilt and/or defocus which records and/or reproduces information on an optical recording medium, the apparatus having a tilt and/or defocus detector for detecting the tilt and/or defocus of an optical recording medium; and a recording compensator for compensating for the recording pulse having a predetermined recording pattern, using a predetermined scheme with respect to tilt and/or defocus detected by the tilt and/or defocus detector.

BRIEF DESCRIPTION OF THE DRAWINGS

The above objects and advantages of the present invention will become more apparent by describing in detail preferred embodiments thereof with reference to the attached drawings in which:

FIG. 1 illustrates coma aberration with respect to wavelength and numerical aperture (NA);

FIG. 2 illustrates changes in peak intensity with respect to tilt;

FIG. 3 illustrates changes in spot size with respect to tilt;

FIG. 4 illustrates changes in a maximum temperature-to-write power ratio with respect to tilt;

FIG. 5 illustrates changes in a maximum temperature-to write time ratio with respect to tilt;

FIG. 6 illustrates changes in peak intensity with respect to defocus;

FIG. 7 illustrates changes in spot size with respect to defocus;

FIG. 8 illustrates changes in beam profile when defocus and tilt occur at the same time;

FIG. 9 illustrates changes in the beam spot size and peak intensity when the defocus and tilt occur at the same time;

FIG. 10 illustrates changes in the recording mark length-to-write power ratio with respect to the tilt;

FIG. 11 illustrates changes the recording mark width-to-write power ratio with respect to the tilt;

FIG. 12A is a table showing changes in the maximum temperature, the length of a recording mark, and the width of a recording mark for each write power with respect to tilt when the wavelength is 650 nm, and FIG. 12B is a table for the same when the wavelength is 400 nm;

FIG. 13 illustrates changes in the recording mark length-to-write time ratio with respect to the tilt;

FIG. 14 illustrates changes in the recording mark width-to-write time ratio with respect to tilt;

FIG. 15A is a table showing changes in the maximum temperature, the length of a recording mark, and the width of a recording mark for each write time with respect to tilt when the wavelength is 650 nm, and FIG. 15B is a table showing the same when the wavelength is 400 nm;

FIG. 16 illustrates the compensation effect of write power when the defocus is 0.25μm and 0.5μm;

FIG. 17 illustrates compensation write powers with respect to defocus;

FIG. 18 is a table showing changes in the shift amount of a write pulse, the length of a recording mark and the width of a recording mark for each write power with respect to tilt and/or defocus;

FIG. 19 illustrates the compensation effect of write power when the tilt is 0.5°, and when the tilt is 0.5° and the defocus is 0.25μm.

FIG. 20 illustrates the compensation effect with respect to write power and write time when the tilt is 0.5°;

FIG. 21A and FIG. 21B illustrate recording patterns of a write pulse used in tilt and/or defocus compensation according to the present invention;

FIG. 22 is a table showing changes in the shift amount of a recording pulse, the length of a recording mark and the width of a recording mark for each write power with respect to tilt;

FIG. 23 illustrates the compensation effect of the length of a recording mark and width of a recording mark by write power when the tilt is 0.5°;

FIG. 24 illustrates the compensation effect of the length of a recording mark and width of a recording mark with respect to changes in the write power and write time when the tilt is 0.5°;

FIG. 25 illustrates the recording compensation effect when the defocus is 1 μm in a 2.6 GB digital versatile disc-random access memory (DVD-RAM);

FIG. 26 illustrates the recording compensation effect when the tilt is 1.0°in a 2.6 GB DVD-RAM;

FIG. 27 illustrates change in jitters with respect to the recording compensation effect when the tilt is 1.0°in a 2.6 GB DVD-RAM;

FIG. 28 is a flowchart of a tilt compensation method according to an embodiment of the present invention;

FIG. 29 is a flowchart of a tilt and defocus compensation method according to another embodiment of the present invention;

FIG. 30 is a block diagram of a tilt compensation apparatus according to an embodiment of the present invention; and

FIG. 31 is a block diagram of a tilt and defocus compensation apparatus according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Hereinafter, embodiments of the present invention will be described in detail with reference to the attached drawings. The present invention is not restricted to the following embodiments, and many variations are possible within the spirit and scope of the present

5   invention. The embodiments of the present invention are provided in order to more completely explain the present invention to anyone skilled in the art.

As shown in FIG. 2, when tilt occurs, the incidence beam peak intensity rapidly decreases when the wavelength is 400 nm. Therefore, it is necessary to compensate for write power and also to compensate for erase power, to a degree.

10   In addition, as shown in FIG. 3, the increase in beam spot size with respect to tilt is moderate at a wavelength of 650 nm, but the increase is rapid at a wavelength of 400 nm. For example, referring to FIG. 3, the same spot size found at a wavelength of 650 nm and a tilt of 1° also occurs at a tilt of 0.3° when the wavelength is 400 nm and the NA is 0.75. Therefore, at 400 nm, beam peak intensity decreases while beam spot size increases, which causes a

15   reduction in power density.

FIGS. 4 and 5 show that a decrease in the maximum temperature with respect to tilt is more rapid at a wavelength of 400 nm than at a wavelength of 650 nm. This result shows that, when recording at the same tilt, there is a prominent energy reduction which is required to form a recording mark for a wavelength of 400 nm.

20   FIGS. 10 and 11 show changes with respect to tilt by measuring the length and width of recording marks in order to compare recording mark shapes with respect to write power at a wavelength of 650 nm and at a wavelength of 400 nm, respectively. The figures show changes in length (L) and width (W) of the recording mark with respect to write power (P_w) at a wavelength of 650 nm and at a wavelength of 400 nm. Specifically, FIG. 10 illustrates the

25   change in the recording mark length-to-write power ratio with respect to tilt, with the recording mark length normalized by the length when tilt is 0° ($L_{tilt}/L_{tilt=0}$). FIG. 10 shows that, as tilt increases, the length of a recording mark (L) decreases more at the wavelength of

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400 nm than at the wavelength of 650 nm, and as write power (P_w) decreases, the length of the recording mark (L) decreases even at the same wavelength of 400 nm. In addition, FIG. 11 illustrates changes in the recording mark width-to-write power ratio with respect to tilt, with the recording mark width normalized by the recording mark width when tilt is 0° ($W_{tilt}/W_{tilt=0}$).

5   FIG. 11 shows that, as tilt increases, the width of recording mark (W) decreases more at a wavelength of 400 nm than at a wavelength of 650 nm, and as write power (P_w) decreases, the width of the recording mark decreases even at the same wavelength of 400 nm. Therefore, the results in FIGS. 10 and 11 show that the decrease in the recording mark length is greater than the decrease in the width, and the decrease at a wavelength of 400 nm is greater than that at a

10   wavelength of 650 nm, when the shape of a recording mark changes with respect to tilt.

For example, the results in FIGS. 10 and 11 show that, when the wavelength is 400 nm and tilt is 0.6°, by changing the write power from 5 mW to 7 mW, the recording mark length decreases by about 72% to 88%, and recording mark width decreases by about 55% to 75%. That is, the results show that the size of a recording mark can be compensated for by

15   compensating the write power. Therefore, a writing strategy can be developed to control the recording waveform utilized for recording data applied to an optical disc system, with compensation being performed by using additional power, such as erase power or write power, to nearly eliminate the effect of tilt.

FIGS. 12A and 12B show tables of changes in the maximum temperature, and in the

20   length and the width of a recording mark for each write power with respect to tilt. The table shown in FIG. 12A shows the changes when the wavelength is 650 nm, and the table shown in FIG. 12B shows the changes when the wavelength is 400 nm.

In addition, based on the detected tilt, compensation can be performed using write time. Thus, for example, the recording mark length can be compensated by adjusting the write time.

25   Therefore, by appropriately adjusting the power level and recording time, tilt compensation is performed so that a recording mark with desired length and width can be recorded.

FIG. 13 shows changes in the recording mark length for different write times (T_W) with respect to tilt, with the recording mark length normalized by the recording mark for a tilt of 0° ($L_{tilt}/L_{tilt=0}$). The figure shows that, as tilt increases, the recording mark length decreases more at a wavelength of 400 nm than at a wavelength of 650 nm. In addition, as write time (T_W)

5   decreases, the recording mark length (L) decreases even at the same wavelength of 400 nm.

FIG. 14 shows changes in the recording mark width for different write times (T_W) with respect to tilt, with the recording mark width normalized by the recording mark for a tilt of 0° ($W_{tilt}/W_{tilt=0}$). The figure shows that, as tilt increases, the recording mark width decreases more at a wavelength of 400 nm than at a wavelength of 650 nm. In addition, as write time

10   (T_W) decreases, the width of a recording mark (L) decreases even at the same wavelength of 400 nm.

FIGS. 15A and 15B show tables of changes in the maximum temperature, and in the length and the width of a recording mark for each write time (T_W) with respect to tilt. The table shown in FIG. 15A shows the changes when the wavelength is 650 nm, and the table

15   shown in FIG. 15B shows the changes when the wavelength is 400 nm.

In addition, as shown in FIG. 6, when tilt and/or defocus occurs, the peak intensity of incidence beam at a wavelength of 400 nm decreases rapidly, and therefore, requiring compensation of the write power. Also, as shown in FIG. 7, the increase in beam spot size is insensitive to tilt and/or defocus at a wavelength of 650 nm, while the beam spot size decreases

20   rapidly at a wavelength of 400 nm with respect to tilt and/or defocus. FIG. 9 shows that such a result is more prominent when defocus and tilt occur together. Therefore, if defocus occurs, beam peak intensity decreases and beam spot size increases, causing the power density to decrease. This is the same result as that produced by tilt.

The effect of defocus on the incident beam is shown in FIG. 16, which illustrates

25   changes in defocus with respect to the shape of mark (the length and width of a recording mark) for each write power for wavelengths 650 nm and 400 nm, respectively. As compared to a normal state, the length and width of a recorded mark both decrease as defocus increases

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when the write power is 6 mW. However, when the decreased length and width of a recording mark due to defocus are compensated for by write power, the same shape as the normal-state mark can be obtained when defocus is 0.25 μm and write power is 6.75 mW, or when defocus is 0.5 μm and write power is 8 mW. Therefore, as shown in FIG. 17, a desired recording

5   mark, that is a recording mark without defocus, can be recorded by using an amount of write power which compensates for the defocus.

FIG. 18 is a table showing the result of measuring the amount of shift of a recording location, and the length of a recording mark and width of a recording mark when tilt is zero, when tilt is 0.5°, and when tilt is 0.5°and defocus is 0.25 μm. Each value is obtained by

10   increasing write power from the 6 mW normal write power in steps of 1 mW. When tilt is zero, there is no need for a write power higher than 6 mW since this is the optimum write power. Similarly, when tilt is 0.5°, there is no need for a write power higher than 8 mW.

FIG. 19 illustrates changes in the length and width of a recording mark with respect to write power when tilt is 0.5°, and when tilt is 0.5° and defocus is 0.25 μm, based on the

15   results in FIG. 18. This figure shows that the difference between the write power required to obtain a normal-state recording mark width and length when tilt is 0.5° ($\triangle$1), is almost the same as the difference between write power required for obtaining the normal-state recording mark width and length when tilt is 0.5° and defocus is 0.25 μm ($\triangle$2).

FIG. 20 illustrates the compensation effected by write time as well as write power when

20   only tilt occurs based on the result in FIG. 19. The figure shows that compensation can be effectively performed when the length of a recording mark is compensated by adjusting the write power, and the width of a recording mark is compensated by adjusting the write time. In particular, compensation can be performed using the ending time of the first pulse (T_{EFP}) and/or the starting time of the last pulse (T_{SLP}) of recording pattern shown in FIG. 21B. In

25   addition, when tilt is compensated by only using write power, the length of a recording mark is adjusted by write power, as described above, and the width of a recording mark can be

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compensated by adjusting the write power of a multi-pulse chain located between the first pulse and the last pulse.

In addition, for non return to zero (NRZI) input data, as shown in FIG. 21A, write pulses in FIG. 21B are generated and then recorded on a disc. FIG 21B shows the starting time of the first pulse (T_{SFP}), the ending time of the first pulse (T_{EFP}), the starting time of the last pulse (T_{SLP}), the ending time of the last pulse (T_{ELP}), and a cooling pulse period (T_{LC}). Also shown are write power P_W (i.e. peak write power), read power (P_r), and bias power (P_b) (i.e. erase power). In addition, FIG. 21B shows the NRZI data as including marks and spaces, with the laser diode being off during the spaces. When a disc is a digital versatile disc (DVD), each mark of NRZI data has a length of 3T, 4T, ..., 14T, with T being 1-bit length. The NRZI data is recorded only by changing the number of multi-pulses without changing the first pulse, the last pulse, and a cooling pulse.

That is, the recording pattern according to a DVD specification includes the first pulse, a multi-pulse chain, and the last pulse. The first rising edge of the first pulse of basic recording pulses occurs a predetermined time after the rising edge of a recording mark. The rising edge of the first pulse can be shifted before and after in units of 1 nanosecond (ns). The rising edge of the last pulse can be shifted also before and after in units of 1 ns. A multi-pulse chain is divided into a plurality of short pulses to reduce accumulation of a heat at the latter part of a recording mark in order to prevent the occurrence of deformation in a recording mark. Therefore, when NRZI input data are recorded as marks and spaces on a disc using a recording pulse having the recording pattern shown in FIG. 21B, the starting point of a recorded mark is shifted by beam shift due to tilt. To compensate for this, the recording pattern must be shifted with respect to tilt.

FIG. 22 shows changes in the recording pattern shown in FIG. 21B with respect to tilt. These changes include changes in the recording location, the shift amount, and the recording mark length and the width with respect to tilt and write power. FIG 22 shows that, as tilt increases, the amount by which the recording location of a recording mark is shifted increases

and the length and width decrease. In addition, as write power increases for the same tilt, the amount by which the recording location of a recording mark is shifted decreases and the length and width increase. As shown in FIG. 22, when tilt is zero, there is no need for a write power higher than 6 mW, and when tilt is 0.5°, there is similarly no need for a write power higher

5   than 8 mW. In addition, when tilt is 1.0°, recording cannot be performed with a write power of 6 mW or 7 mW.

FIG. 23 shows the compensation effect of a recording pattern (i.e. the length and the width of a recording mark) by write power when tilt is 0.5°, based on the result in FIG. 22, with the length and width normalized with respect to length and width for a write power of 6

10   mW and a tilt of 0°. FIG. 23 shows that when tilt occurs, the length and the width of a recording mark increase as write power increases, and the length of a recording mark is effectively compensated for write power. For example, when write power is 6 mW, the length of a recording mark corresponds to 85% of the normal value and the width of a recording mark corresponds to 75% of the normal value. Therefore, for the same write power, the

15   compensation is more effective as to the length than as to the width.

FIG. 24 illustrates the compensation effect of the recording pattern by write time as well as write power when tilt is 0.5°, based on the result in FIG. 23. The figure shows that compensation for the length of a recording mark can be effectively adjusted by write power, while compensation for the width of a recording mark can be effectively adjusted by write

20   time. In particular, the compensation of the width is performed using the ending time of the first pulse (T_{EFP}) and/or the starting time of the last pulse (T_{SLP}) of the recording pattern shown in FIG. 21B. In addition, when tilt is compensated only by adjusting the write power, the width of a recording mark can be compensated by adjusting the write power of the multi-pulses located between the first pulse and the last pulse.

25   In addition, by storing, in advance, data on the write power and/or write time needed to compensate for the shift amount of the recording pattern, and the length and the width of a recording mark with respect to tilt based on the result in FIG. 22 in memory, compensation

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can be adaptively performed based on a detected tilt. In addition, the memory can store data on write power and/or write time to compensate for the shift amount of the recording pattern, and the length and the width of a recording mark according to the recording pattern (the length of a recording mark) of input data as well as tilt.

5   FIG. 25 is the result of an experiment to compensate, by write power, for a detected defocus using a 2.6 GB DVD-RAM. FIG 25 shows the same tendency as the result of simulation in FIG. 16. The power of a 2.6 GB DVD-RAM in a normal state is 12 mW (write power), 3.0 mW (bias power), 5.5 mW (read power). When 0.1 μm defocus occurs, the length and the width of a recording mark are compensated by an increase in the write power.

10   FIG. 26 shows changes in the length and the width of a recording mark with respect to compensation by write power when a tilt of 1° occurs, using the same 2.6 GB DVD-RAM as the disc in FIG. 25. The figure shows that when tilt occurs, the length and the width of a recording mark are compensated by controlling the write power.

          FIG. 27 shows the change in jitter with respect to power both without tilt, and with a tilt of 1°. In a normal state where tilt does not occur, jitter hardly occurs even as write power increases. However, when there is tilt, the jitter amount decreases as write power increases.

          In conclusion, when only defocus occurs, it can be compensated for by only adjusting write power. However, when defocus and tilt occur together, the shift of beam by tilt is compensated for by shifting the entire recording pattern, the length of a recording mark is compensated for by adjusting write power, and the width of a recording mark is compensated for by adjusting write time and particularly by the ending time of the first pulse (T_{EFP}) and/or the starting time of the last pulse (T_{SLP}) in the recording pattern. In addition, when defocus and tilt are compensated for only by adjusting write power, the length of a recording mark is adjusted by write power, the width of a recording mark can be adjusted by write power of multi-pulses located between the first pulse and the last pulse.

          FIG. 28 is a flowchart of a method of compensating for tilt according to an embodiment of the present invention. In step S101, tilt is detected, and in step S102, it is determined

whether or not tilt is zero (tilt=0°). While not shown, step S102 could also determine whether or not tilt is $\alpha°$ by considering the margin of tilt ($\alpha°$).

In step S103, when detected tilt is not zero, the recording pattern of the write pulse is shifted in the direction for compensating for tilt. The length and the width of a recording mark are compensated so that the effect of tilt is nearly eliminated in step S104. In step 104, compensation for the length of a recording mark is provided by adjusting the write power, and the compensation of the width of a recording mark is provided by adjusting the write time, and particularly by the ending time of the first pulse (T_{EFP}) and/or the starting time of the last pulse (T_{SLP}) in the recording pattern. In addition, when tilt is compensated only by adjusting write power, the length of a recording mark is adjusted by write power, the width of a recording mark can be adjusted by write power of the multi-pulses located between the first pulse and the last pulse.

In step S105, when tilt is zero in step S102, recording is performed by maintaining the power and write time required for recording, which are supplied to a laser diode. However, when tilt is not zero at step S102, recording is performed by applying to a laser diode a write pulse that has write power and/or write time required for recording with respect to detected tilt supplied in the step S104.

In steps S103 and S104, the required shift amount, write power and/or write time can adaptively compensate for the detected tilt by storing, in a memory, data on the write power and/or write time required to compensate the shift amount of the recording pattern, and the recording mark length and the width based on input data of either the tilt or the length of a recording mark.

FIG. 29 is a flowchart of a method of compensating for tilt and/or defocus according to another embodiment of the present invention. In step S201, tilt and/or defocus is detected, and in step S202, it is determined whether or not the detected defocus is equal to or less than a predetermined margin (α μm).

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When the result in step S202 indicates that the detected defocus is greater than a defocus predetermined margin (α μm), write power is adjusted with respect to the detected defocus in step S203. When the result in step S202 indicates that detected defocus is equal to or less than the defocus predetermined margin (α μm), it is then determined in step S204 whether or not the detected tilt in step S201 is equal to or less than a tilt predetermined margin (β°).

When the result in step S204 indicates that tilt is greater than the tilt predetermined margin (β°), the recording pattern of a write pulse is shifted in a direction that is opposite to the direction shifted due to the detected tilt in step S205, and the length and the width of a recording mark are compensated in step S206, nearly eliminating the effect of the detected tilt. In step 206, compensation of the length of a recording mark is provided by adjusting the write power. Compensation of the width of a recording mark is provided by adjusting the write time, and particularly, by the ending time of the first pulse (T_{EFP}) and/or the starting time of the last pulse (T_{SLP}) in the recording pattern. In addition, when tilt is compensated for only by adjusting write power, the length of a recording mark is compensated by adjusting the write power as described above, and the width of a recording mark is compensated by adjusting the write power of the multi-pulses located between the first pulse and the last pulse.

In step S207, when both defocus and tilt are equal to or less than the defocus predetermined margin (α μm) and the tilt predetermined margin (β°), recording is performed by maintaining the power and write time required for recording, which are supplied to a laser diode. Otherwise, recording is performed by applying to the laser diode either a write pulse that has the write power compensated with respect to defocus detected in step S203, or a write pulse having a power and/or time required for recording to compensate the recording mark with respect to the detected tilt.

In step 203, the write power required to compensate for defocus and the required shift amount, as well as the write power and/or write time in steps S205 and S206, can adaptively compensate with respect to the detected tilt and/or defocus by storing, in a memory, data on

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the write power and/or write time required to compensate for the shift amount of the recording pattern, and the length and the width of a recording mark using the detected tilt or the length of a recording mark as input data. In addition, the memory can both store the write power and/or write time, and the amount of shift required for recording to correspond to both a case where

5   defocus and tilt occur together, and a case where defocus or tilt occurs.

FIG. 30 is a block diagram of an apparatus to compensate for tilt according to an embodiment of the present invention. Shown in FIG. 30 are an optical disc 102, a pick-up unit 104, a reproduction signal detector 106, a tilt detector 108, a recording compensator 110, and a laser diode driver 112. The pick-up unit 104, which drives an optical disc 102, includes

10   typical mechanisms for an optical system, which includes an objective lens 1, a half mirror 2, a collimator lens 3, a photo detector 4, a laser driver 5, and, though not shown in the figure, an actuator for focusing and tracking.

In the shown embodiment, the laser diode wavelength of the pick-up unit 104 is equal to or less than approximately 430 nm, which is the wavelength for blue light. In addition,

15   when the thickness of a disc substrate is equal to or greater than 0.3 mm, the NA of the objective lens 1 is equal to or greater than 0.6, and when the thickness of a disc substrate is equal to or less than 0.3 mm, the NA of an objective lens 1 is equal to or greater than 0.7.

The reproduction signal detector 106 detects a reproduction signal in the output signal of the photodetector 4. The tilt detector 108 detects tilt of an optical disc 102, using the

20   reproduction signal supplied by the reproduction signal detector 106 or the output signal of the photodetector 4. The shown tilt detector 108 can be used only for detecting tangential tilt.

The recording compensator 110 generates a recording pulse earlier than it would otherwise be generated to compensate for the amount of shift due to tilt, which is detected by the tilt detector 108, in order to shift the starting point of a recording mark in the direction in

25   which tilt is compensated. In addition, compensation of the length of a recording mark is provided by adjusting write power, while the width of a recording mark is compensated by adjusting the write time. In the shown embodiment, the width of a recording mark is

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compensated by using the ending time of the first pulse (T_{EFP}) and/or the starting time of the last pulse (T_{SLP}) of the recording pattern. In the alternative, when tilt is compensated using only write power, the length of a recording mark is compensated by write power, as described above, and the width of a recording mark can be compensated by adjusting the write power of

5   the multi-pulses located between the first pulse and the last pulse.

In addition, the recording compensator 110 can adaptively compensate for tilt detected in the tilt detector 106 by integrating a memory storing data on the write power and/or write time needed to compensate the shift amount of the recording pattern and the recording mark length and width with respect to tilt. In addition, the data can include the write power and/or

10   write time required to compensate the shift amount of the recording pattern and the recording mark length and width with respect to the length of a recording mark as well as tilt.

The laser diode driver 112 performs recording on the optical disc 102 using the pick-up unit 104 by converting a write pulse signal into a current signal and making the current signal flow through the laser diode 5 during write time with respect to the power level of the write

15   pulse adjusted in the recording compensator 110. That is, when the laser diode is continuously turned on, heat is transferred to the optical disc and the data is recorded as a recording mark.

FIG. 31 is a block diagram of an apparatus for compensating for tilt and defocus according to another embodiment of the present invention. Shown in FIG. 31 are an optical disc 202, a pick-up unit 204, a reproduction signal detector 206, a defocus/tilt detector 208, a

20   recording compensator 210, and a laser diode driver 212. The pick-up unit 204, which drives the optical disc 202, includes typical mechanisms for an optical system, which includes an objective lens 11, a half mirror 12, a collimator lens 13, a photo detector 14, a laser diode 15, and, though not shown, an actuator for focusing and tracking.

In the shown embodiment, the laser diode wavelength of the pick-up unit 204 is equal

25   to or less than approximately 430 nm, the wavelength of blue light. In addition, when the thickness of a disc substrate is equal to or greater than 0.3 mm, the NA of the objective lens 11

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is equal to or greater than 0.6, and when the thickness of a disc substrate is equal to or less

than 0.3 mm, the NA of an objective lens 11 is equal to or greater than 0.7.

The reproduction signal detector 206 detects a reproduction signal in the output signal

of the photodetector 14. The defocus/tilt detector 208 detects defocus and/or tilt using the

5   reproduction signal supplied by the reproduction signal detector 206 or the output signal of the

photodetector 14. The shown tilt detector 208 can only be used for detecting tilt in tangential.

The recording compensator 210 generates a write pulse, which uses an adjusted write

power to compensate for a defocus detected in the defocus/tilt detector 208, and generates a

recording pulse earlier to compensate for the amount of shift due to the detected tilt, in order

10   to shift the starting point of a recording mark when tilt is detected. In the shown embodiment,

compensation of the length of a recording mark is adjusted by write power, and compensation

of the width of a recording mark is adjusted by write time. In addition, the width of a

recording mark is compensated for by using the ending time of the first pulse (T_{EFP}) and/or the

starting time of the last pulse (T_{SLP}) of the recording pattern. In the alternative, when tilt is

15   compensated for only using write power, the length of a recording mark is compensated using

write power, as described above, and the width of a recording mark is compensated by

adjusting the write power of the multi-pulses located between the first and last pulse in the

write pulse.

In addition, the recording compensator 210 can adaptively compensate for tilt and/or

20   defocus detected in the defocus/tilt detector 206 by integrating a memory storing data on write

power required for a detected defocus, and write power and/or write time required to

compensate the shift amount of the recording pattern, and the length and the width of a

recording mark with respect to the tilt or the length of a recording mark in input data.

The laser diode driver 212 performs recording on the optical disc 202 using the pick-up

25   unit 204 by converting a write pulse signal, the write pulse signal having been compensated

with respect to power level in the recording compensator 210, into a current signal, and

making the current flow through the laser diode 15 during write time. That is, when the laser

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diode is continuously turned on, heat is transferred to the optical disc and recording data is recorded as a recording mark.

According to the present invention, the power (write power, erase power, etc.) level required for recording must be increased by a predetermined amount with respect to detected tilt and/or defocus. In addition, the write time is adjusted. As a result, a temperature similar to that when there is no tilt and/or defocus can be obtained, and therefore, the desired size (length, width) of a recording mark can be recorded.

As described above, according to the present invention, since recording is compensated by adjusting the power level and/or recording time required for recording with respect to detected tilt and/or defocus, a recording mark having a desired size (length, width) can be recorded, and therefore, the present invention is appropriate for a high-density optical system.

Although a few preferred embodiments of the present invention have been shown and described, it would be appreciated by those skilled in the art that changes may be made in this embodiment without departing from the principles and spirit of the invention, the scope of which is defined in the claims and their equivalents.